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POSTER

Geophysics

The Origin of Peak-Ring Basins on the Moon: Working Hypothesis and Path Forward in Using Observations to Constrain Models of Impact Basin Formation

Impact basins provide windows into the Moon's crustal structure and stratigraphy; however, interpreting the origin of impact basin materials requires constraints on the processes controlling basin formation and morphology. Peak-ring basins (exhibiting a rim crest and single interior ring of peaks) provide important insight into the basin-formation process, as they are transitional between complex craters with central peaks and multi-ring basins. New image and altimetry data from the Lunar Reconnaissance Orbiter as well as a suite of remote sensing datasets have permitted a reassessment of the origin of lunar peak-ring basins [e.g., 1-5]. We synthesize our morphometric, spectroscopic, and gravity observations of lunar peak-ring basins and describe a working hypothesis on the formation of peak rings that involves interactions between inward collapsing walls of the transient cavity and large uplifts of the crust and mantle that occur in the center of the basin. Our observations also demonstrate the importance of impact melting in modifying the interior morphology of large impact craters on the Moon. Major facets of our observations are then qualitatively compared and discussed in context of current numerical simulations of peak-ring basin formation in order to plot a course for future model refinement and development. We find that several major areas should be a focus for future numerical modeling of impact basins, including: 1) Central peak/Peak-ring dimensions: Systematic, quantitative comparisons between measurements of observed peak dimensions (e.g., height and diameter) and model predictions over the full sequence of peak morphologies are crucial. 2) Impact melt: Assessment of the post-impact modification of basin topography by impact melt (e.g., cooling and vertical contraction) may shed light on current inconsistencies between models and observations. 3) Peak-ring sampling depth and physical characteristics: More explicit predictions of sampling depth (or stratigraphic uplift) of central peaks and peak rings for a range of target and impactor conditions are needed, with more emphasis on non-terrestrial bodies. Important are estimates of peak-shock pressures and the physical characteristics of lithologies predicted to comprise the peak ring. 4) Faulting: Improved models incorporating the localization effects of faults on transient weakening and transient cavity collapse. Inclusion of discrete fault movements within the collapsing rim should improve the kinematic predictions of peak-ring formation. 5) Deep crustal and mantle structure: Reconciliation of current inconsistencies in observed crustal structure over peak-ring basins, as interpreted from GRAIL gravity data, and modeled crustal structure.

Geophysics

Moon-Forming Impact Ejecta as the Source of the Earliest Lunar Bombardment

The earliest phase of lunar bombardment, defined by pre-Nectarian (pN) craters and basins on the Moon, has long been a mystery. Many argue pN impact events were derived from a long-lived leftover planetesimal population residing in the terrestrial planet region (Neukum and Ivavov 2001; Morbidelli et al. 2013). Problems with this model, however, have recently emerged. Analyses of ancient pN cratered terrains, as well as hydrocode models of South Pole Aitken (SPA) basin formation, suggest pN projectiles struck the Moon at ~ 10 km/s, 1.5-2 times lower than expectations from existing dynamical models of leftover planetesimals (Walsh et al. 2011; Marchi et al. 2012; Potter et al. 2013). Our own collisional and dynamical evolution simulations of leftover planetesimals have also had difficulty reproducing the characteristic signatures of pN craters/basins. Here we argue for an unexplored bombardment scenario that fits within the framework of planet and lunar formation models. We postulate that most pN impacts were produced by the relatively late return of ejecta from the giant impact (GI) that created the Moon. The GI was probably the biggest youngest impact to ever take place in the terrestrial planet region, and simulations indicate that several percent of an Earth mass was ejected out of cis-lunar space by this event (e.g., Jackson and Wyatt 2012; Canup 2012). Tracking this material using a suite of collisional and dynamical models, we find GI ejecta returns in some abundance to strike the Moon at ~10 km/s over an interval of many tens of Myr. En route to the Moon, the population undergoes extensive collisional evolution, enough to reproduce the wavy shape of the observed pN crater size frequency distributions upon impact. Our model results predict that the oldest pN- and SPA-cratered terrains formed ~8 and 15 Myr after the GI, respectively. SPA basin may have even formed earlier than these times, which would explain the absence of SPA-produced secondary craters on nearby pN terrains (Bottke et al. 2013). This would require processes on SPA to erase 20 < D < 100 km craters for ~7 Myr after SPA formed, a plausible scenario considering the nature of the early lunar crust and lunar magma ocean (Elkins-Tanton et al. 2011). We also find that considerable GI ejecta hit the Moon prior to the oldest pN terrains, with the projectiles presumably slamming into a thin hot mushy lunar crust. The consequences of such impact events are unknown, but we suspect they would leave behind features similar to the flat palimpsest-like basins on Callisto. Such outcomes could explain why several prominent pN basins discussed by Wilhelms (1987), such as Procellarum, Australe, and Tranquillitatis, lack the topographic and gravity signatures of younger basins defined by GRAIL data. Accordingly, our results provide key constraints on the time-varying nature of the earliest lunar crust, the evolution of the lunar magma ocean, the size frequency distributions of both GI ejecta and leftover planetesimals, and planet formation itself.

Geophysics

A Revisit to Magnetic Sounding of the Lunar Electrical Conductivity Profile with Apollo 15 Data

In the 1970s and 80s, studies using the Apollo surface and orbital magnetic field observations have estimated the size of the metallic core and the deep lunar electrical conductivity profile of the Moon. In these early magnetic sounding studies, the Apollo Lunar Surface Magnetometer (LSM) data were limited to those collected by the Apollo 12 mission. In recent years, the Apollo magnetic field data have been restored from their original, obsolete forms. The data restoration effort has made available the entire set of Apollo subsatellite magnetometer data and some of the Apollo 15 LSM data for scientific analysis. This study presents the transfer function analysis based mainly on the Apollo 15 magnetic field observations to infer the deep lunar electrical conductivity profile. The results are compared with those previously demonstrated by studies based on Apollo 12 and Explorer 35 observations.

Geophysics

Thermal Inertia of the Moon from Diviner Lunar Radiometer Measurements

Thermal inertia is a quantity that characterizes a material's resistance to changes in temperature. In remote sensing, thermal inertia is often used to infer physical properties of planetary surfaces by observing temperature oscillations occurring on known time scales. Unconsolidated particulate materials such as the lunar regolith tend to have low thermal inertia, and consolidated materials such as boulders and bedrock tend to have high thermal inertia. Long-period temperature oscillations (such as seasonal cycles) sense greater depths than short-period oscillations (such as a lunar eclipse); this allows retrieval of depth profiles of thermal inertia. Thus, it is possible to derive information about the history and present state of a geologic unit by measuring its temperature variations on various time scales. While the Moon's temperature has been measured for nearly a century, the Diviner Lunar Radiometer provides a dataset of unprecedented accuracy and coverage, as well as spatial and temporal resolution. We used Diviner data spanning nearly five years (60 lunar diurnal cycles) to constrain models of regolith thermal inertia, and mapped the results at a resolution of 128 pixels per degree from -70 to +70 degrees latitude. As we will show, the results clearly differentiate old and young craters by their relative thermal inertia values, and show regional and global patterns indicating the imprint of regolith formation by impacts over time. This new dataset has potential applications to a broad range of problems in lunar science, and the technique is widely applicable to airless bodies throughout the Solar System.

Geophysics

A BALLISTIC MODEL FOR ANTIPODAL IMPACT MELT DEPOSITS ON THE MOON.

Data from infrared and visual LRO observations have revealed an anomalous area of ponded smooth deposits covering > 3000km2 at 41°N, 167°E (farside) of the Moon. This region of smooth deposits is the result of a momentary impact melt event around 100Ma and its origin is tied to the creation of the 85km diameter Tycho crater (43°S, 349°E). The location of the smooth deposits region is very close to the antipode of the Tycho crater. The antipodal field describes a topography of ponded basins (depth ≈5m) emplaced in what was then already extant crater arrays and indicates scenes of vigorous slushing and low viscosity flow patterns of impact melts commonly spilling into uphill gushes.   The Tycho crater originated with an oblique angle (30° to 45°) impact of a huge bolide (≈10km) striking the Moon at typical solar system speeds (≈20km/s). The contact phase (≈1s) spouted high velocity jets at low angle and the following excavation phase (≈1minute) produced a spallation dust cloud and a fast expanding ejecta curtain shaped as a truncated inverted cone. Ejecta debris size categories and displacement distances adhere to the statistics of power law distributions such that a large fraction of ejecta material is found as sub-millimeter dust. 2-body ballistics for reconnection trajectories onto a spherical shaped Moon surface shows that antipodal path times are about 2 hours for an initial elevation angle of 25° (from the horizon), and that 45° is the upper limit for the elevation angle for any antipodal connection. Admitting the rotation of the Moon (≈27.3 Earth days) moves the location of Tycho's antipode to the observed center of impact melt region. Artemieva (2013) envisions the impact melt deposits as the result of ballistic antipodal flights of partially molten, man sized (≈1m) blobs bursting open on re-impact. This scenario requires a non-standard ejecta size distribution statistics and would necessitate a contemporary modification of the cratering scene which is not observed. We propose that the impact making the Tycho crater produced a vast and dense cloud of sub-millimeter sized particles where a sizeable fraction of these dust particles had a speed ≈ 2km/s and an initial ejection elevation angle ≈ 20°. The path refocusing aspect of the antipode flight admitted for an incessant embedding of these high speed dust particles into the regolith base during which the kinetic energy was dissipated into local heating through a frictional slow down against the burying soil (during the span of ≈ 1/2hour). Our one dimensional melt flow heat balance model incorporating radiation losses (temp4), heat loss to underlying soil, phase transformation (liquid-solid), and change of temperature of the embedding dust results in the onset of a lava flow down a 10° slope starting about 20 minutes after the re-impact event commences.

Geophysics

Theia's provenance: dynamical evolution of a late Impactor

In the Solar System's early history many processes have been proposed that depend on the dynamical state of the planets. Our study considers the possible dynamical states that produce a late Giant Impact (70 − 110 Myr) to form the Earth-Moon system. We investigate within the semimajor axis and eccentricity parameter space to determine the possible outcomes of a 5 terrestrial planet model of the Solar System for 3 different mass ratios (8:1, 4:1, and 1:1) of the Earth-Moon progenitors. Using angular momentum conservation, an initial condition is prescribed for the progenitor masses while using initial conditions for the other Solar System bodies from a well-known common epoch. Additionally we test the 4:1 mass ratio with a different giant planet configuration akin to the Nice model. We find local regions of our parameter space are more conducive to the outcome of a late Giant Impact. Mean motion resonances (MMRs) are identified between the terrestrial planets and used along with secular effects from the giant planets to indicate likely regions where a Giant Impact would occur. We characterize our results considering the estimated time of the Giant Impact, the resultant mass distribution of terrestrial planets, and the post collision mean angular momentum deficit (AMD). Case studies are presented illustrating the various possible outcomes with respect to their AMD relative to the current Solar System. Our statistical results show that a Nice model giant planet configuration can affect the occurrence of Giant Impacts and a restricted region of parameter space exists for all considered cases. The implications on planet formation scenarios and implicit habitability will also be discussed.

Geophysics

Lunar Atmosphere Probe Station: A Proof-of-Concept Instrument Package for Monitoring the Lunar Atmosphere

The lunar exosphere is the exemplar of a plasma near the surface of an airless body. Exposed to both the solar and interstellar radiation fields, the lunar exosphere is mostly ionized, and enduring questions regarding its properties include its density and vertical extent, the extent of contributions from volatile outgassing from the Moon, and its behavior over time, including response to the solar wind and modification by landers. Relative ionospheric measurements (riometry) are based on the simple physical principle that electromagnetic waves cannot propagate through a partially or fully ionized medium below the plasma frequency, and riometers have been deployed on the Earth in numerous remote and hostile environments. A multi-frequency riometer on the lunar surface would be able to monitor, in situ, the vertical extent of the lunar exosphere over time.We provide an update on a concept for a riometer implemented as a secondary science payload on future lunar landers, such as those recommended in the recent Planetary Sciences Decadal Survey report or commercial ventures. The instrument concept is simple, consisting of an antenna implemented as a metal deposited on polyimide film and receiver. We will present results from a performance test of the spectrometer and deployable antenna. The Lunar University Network for Astrophysical Research consortium is funded by the NASA Lunar Science Institute to investigate concepts for astrophysical observatories on the Moon.Part of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA.

Geophysics

Accretion of the Moon from disk produced by non-canonical impacts

The Earth's Moon is thought to have formed by accretion from a disk generated by a giant impact onto the Earth. In the canonical case, the impactor is a Mars-size object and the disk is composed primarily of impactor material (e.g. Canup 2004, 2008). Since the impactor likely had a composition different from that of the Earth, this seems at odds with the identical isotopic compositions of the Earth's mantle and the Moon. Pahlevan & Stevenson (2007) suggested that material exchange between the disk's and Earth's atmospheres could modify the composition of the disk to match that of the silicate Earth, resulting in compositional equilibration in O(100) years, a timescale much longer than that predicted for lunar accumulation from the disk (Ida et al. 1997, Kokubo et al. 2000).Using a more accurate modeling of the Moon's accretion from the protolunar disk, accounting in particular for the presence of vapor in the disk, we have shown that the Moon's accretion from the disk occurs on a timescale compatible with that required for equilibration to occur (Salmon & Canup 2012). However, it may be difficult for equilibration to occur without simultaneously depleting the disk of its mass (Melosh 2009). In addition, in our model a substantial portion of the Moon accumulates rapidly after the impact from material placed into distant orbits, and at least this portion appears unlikely to equilibrate with the Earth.Recently, new types of impacts have been proposed, involving either larger impactors (Canup 2012) or high-velocity impacts on a fast-spinning Earth (Cuk & Stewart 2012), and resulting in a protolunar disk whose composition is much closer to that of the post-impact Earth. These impacts, however, leave the Earth-Moon system with an excess of angular momentum. Subsequent capture of the Moon into the evection resonance has been argued to be capable of reducing the angular momentum of the Earth-Moon system by a factor of 2, making it compatible with its current value (Cuk and Stewart 2012).We have identified two main concerns with these non-canonical impacts: 1) they form more compact disks, with most of the mass located inside the Roche limit at 2.9 R_Earth. Incorporation of material from this inner region into the Moon is rather inefficient (Salmon and Canup 2012), so that formation of Moon-size objects may be compromised; 2) capture into the evection resonance seems possible only for a narrow range of orbital parameters. Previous work assumed that the Moon formed around 3.8 R_Earth (Cuk & Stewart 2012), while we found that the Moon forms in fact around 6 R_Earth.We have modeled the accretion of the Moon from non-canonical disks, and find that forming a Moon-size object requires very massive disks that may only be achievable by the impact-scenario of Canup (2012). We also find that the Moon is driven even farther away than in canonical cases, which may compromise subsequent capture into the evection resonance.

Geophysics

Are Density Variations on the Lunar Mantle Detectable with GRAIL Gravity Data?

When the lunar topographic contribution is removed from a lunar gravity model it provides a Bouguer disturbance that indicates mass excesses and deficiencies in the crust and possibly the upper mantle. Identifying gravity signals that originate at greater depth is a challenge. We try to determine if some of the larger lunar Bouguer disturbances are below the lunar crust and what affect that might have on the global Bouguer signal.

Geophysics

THE OXFORD SPACE ENVIRONMENT GONIOMETER

Measurements of the light scattering properties of the regolith of airless bodies in the Solar system, across wavelengths from the visible to the far infrared are essential to understanding their surface properties. This presentation will describe a new experimental setup, the Oxford Space Environment Goniometer (OSEG). The OSEG allows phase function measurements of samples to be made under vacuum (<10-4 mbar) whilst enclosed by a cooled (<150 K) radiation shield. The cooled radiation shield reduces the thermal background allowing phase measurements from the visible to the thermal infrared to be made. This work was originally motivated by the need for new emission phase function measurements to support analysis of data currently being returned by the Diviner Lunar Radiometer (Diviner) instrument. Diviner is a nine-channel mapping radiometer onboard NASA's Lunar Reconnaissance Orbiter. It has channels ranging from the visible to the far infrared (>400_m), with three mineralogy channels centered on the mid-infrared (8_m) [1].To fully interpret the brightness temperatures measured by a thermal infrared instrument requires a 3D thermophyscal model [e.g. 2,3]. However these models are dependent on knowledge of the phase function of scattered and emitted radiation across the visible, near and thermal infrared. These models typically assume that infrared radiation is scattered isotropically from the lunar surface. Although generally the models are in very good agreement with the measured brightness temperatures of the lunar surface, there are some discrepancies [2]. One possible reason for these discrepancies is that the scattering properties of the regolith in the thermal infrared are incorrectly estimated by the models. Although significant progress is being made in determining the scattering properties of the lunar soil in the visible and near infrared [e.g. 4,5], there is still limited or no data available on the scattering properties in the thermal infrared. Therefore, we are developing an automated, vacuum compatible goniometer (angular measuring device) system capable of measuring both the bidirectional distribution reflectance function and directional emissivity in the thermal infrared of samples under simulated lunar thermal conditions in the laboratory. The first use of the system will be to provide support for measurements made by the Diviner instrument in the thermal infrared. Some very initial measurements of the directional emissivity for a variety of different surface textures will be shown. References[1] Paige, D. A. et al., Space Sci. Rev.150, 125-160, 2009. [2] Paige, D. A. et al., Science, 330, 479, 2010. [3] Vasavada, A.R. et al., Icarus, 141, 179, 1999. [4] Foote, E. J., LPSC XXXXIII abstract #2357, 2012. [5] Pommerol, A. et al., Planetary and Space Science., 59, 1601-1612, 2011

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Geophysics

Fault Dislocation Modeling of Tectonic Landforms in Mare Frigoris

Previous work suggested that large-scale nearside basin-localized extensional tectonism on the Moon ended ~3.6 billion years ago and mare basin-related contractional deformation ended ~1.2 billion years ago [Lucchitta and Watkins, 1978; Solomon and Head, 1979, 1980; Hiesinger et al., 2003]. Lunar Reconnaissance Orbiter Camera (LROC) Narrow Angle Camera (NAC) [Robinson et al., 2010] high resolution (50-200 cm/pixel) images enable the detailed study of lunar tectonic landforms and further insight into the evolution of stresses. Populations of wrinkle ridges, lobate scarps, and graben are now observed at scales much smaller than previously recognized, and their morphology and stratigraphic relationships imply a complex deformational history [Watters et al., 2010, 2012]. Mare Frigoris (~45°N-60°N, 40°W-40°E) is one such area with abundant tectonic landforms now revealed by LROC [Williams et al., 2014].The most common tectonic landforms in mare basins are sinuous wrinkle ridges that have up to hundreds of meters of relief and are interpreted as folded basalt layers overlying thrust faults [Plescia and Golombek, 1986; Golombek et al., 1991; Schultz, 2000; Watters, 2004; Watters and Johnson, 2010]. They often consist of a narrow, asymmetric ridge atop a broad arch and sometimes occur radial to or concentric with the centers of some mare basins. Wrinkle ridges with these patterns have previously been associated with mascons – dense concentrations of mass identified by positive gravity anomalies. The thick basaltic lava thought responsible for lunar mascons causes flexure and subsidence to form wrinkle ridges [Solomon and Head, 1979, 1980]. However, Mare Frigoris is not associated with a mascon [Zuber et al., 2013], yet wrinkle ridges deform the mare basalts there [Whitford-Stark, 1990; Williams et al., 2014]. The origin of compressional stresses in non-mascon environments remains an outstanding question.A key step to better understanding the occurrence of wrinkle ridges in non-mascon basins is characterizing the behavior of the underlying faults. We expand upon methods used in Williams et al. [2013] and apply fault dislocation modeling to estimate geometries and displacements for selected wrinkle ridge faults in Mare Frigoris. Digital terrain models (DTMs) derived from LROC NAC stereo pairs [Tran et al., 2010] are used to constrain fault models. Using the system of analytical equations for deformation of a half-space defined by Okada [1985, 1992], we apply a genetic algorithm to invert ridge relief for fault parameters including dip angles, displacements, and depths of faulting along fault segments. Preliminary results for a portion of an S-shaped wrinkle ridge in western Mare Frigoris include maximum depths of faulting within the upper ~1-2 km, displacements of up to 200 m, and shallow (<40°) dip angles. These preliminary modeled values are comparable to estimates for other lunar and martian wrinkle ridges [e.g. Plescia and Golombek, 1986; Golombek et al., 1991; Schultz, 2000; Watters, 2004; Watters and Johnson, 2010], and suggest this faulting is likely confined to within the mare fill and not rooted deeply in anorthositic crust.

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Geophysics

Global Surface Temperatures of the Moon

The Diviner Lunar Radiometer Experiment on NASA's Lunar Reconnaissance Orbiter (LRO) has been systematically mapping the global thermal state of the Moon since July of 2009. The instrument has acquired solar reflectance and mid-infrared radiance measurements in nine spectral channels spanning a wavelength range from 0.3 to 400 _m (Paige et al., 2010a). With nearly five years of data, the density of observations both spatially and in localtime is high enough that global diurnal temperatures can be adequately resolved to create global maps of surface temperatures. Nadir observations of radiance from the 7 infrared spectral channels are used to derive bolometric brightness temperatures, a measure of the spectrally integrated flux of infrared radiation emerging from the surface (Paige et al., 2010b). For the purposes of quantifying the overall heat balance of the surface and comparing with available models, the bolometric brightness temperature is the most fundamental and interpretable measurable quantity. With the diurnal temperatures determined for each 0.5 degree of binned data we create instantaneous global maps of surface temperatures for a given subsolar point.These systematic observations of the global thermal state of the Moon and its diurnal variability provides the ability to characterize the surface energy balance and develop an understanding of how the lunar regolith stores and exchanges heat. The highly insulating nature of the surface, the lack of an appreciable atmosphere to buffer surface temperatures, and slow rotation, result in an extremely complex thermal environment, especially when illumination angles are low such as in the vicinity of the dawn and dusk terminators and at high latitudes and the polar regions, where topography dominates the surface temperatures. Temperatures can vary by >100 K between shadowed and sunward facing slopes down to the smallest length scales resolved. In addition to topographic effects, daytime temperatures, which are in near-equilibrium with the solar flux, are influenced by radiative properties of the surface. Nighttime temperatures however are determined by the radiation of sensible heat stored in the subsurface during the day and therefore are sensitive to the thermophysical properties of the regolith (Bandfield et al., 2011, Vasavada et al., 2012).